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SUSY Les Houches Accord 2

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Abstract

The SUSY Les Houches Accord provides a common interface that conveys spectral and decay information between various computer codes used in supersymmetric analysis problems in high energy physics. Here, we propose extensions of the conventions of the first SUSY Les Houches Accord [1] to include various generalisations: the minimal supersymmetric standard model (MSSM) with violation of CP, R-parity, and flavour, as well as the simplest next-to-minimal supersymmetric standard model (NMSSM).

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Contents

1 Introduction

Supersymmetric extensions of the Standard Model rank among the most promising and well-explored scenarios for New Physics at the TeV scale. Given the long history of supersymmetry and the number of people working in the field, several different conventions for defining supersymmetric theories have been proposed over the years, many of which have come into widespread use. At present, therefore, no unique set of conventions prevails. Rather, different conventions are adopted by different groups for different applications. In principle, this is not a problem. As long as everything is clearly and consistently defined, a translation can always be made between two sets of conventions.

However, the proliferation of conventions does have some disadvantages. Results obtained by different authors or computer codes are not always directly comparable. Hence, if author/code A wishes to use the results of author/code B in a calculation, a consistency check of all the relevant conventions and any necessary translations must first be made – a tedious and error-prone task.

To deal with this problem, and to create a more transparent situation for non-experts, the original SUSY Les Houches Accord (SLHA1) was proposed [1]. This accord uniquely defines a set of conventions for supersymmetric models together with a common interface between codes. The most essential fact is not what the conventions are in detail (they largely resemble those of [2]), but that they are consistent and unambiguous, hence reducing the problem of translating between conventions to a linear, rather than a factorial, dependence on the number of codes involved. At present, these codes can be categorised roughly as follows (see [3, 4] for a quick review and on-line repository):

- Spectrum calculators [5–8], which calculate the supersymmetric mass and coupling spectrum, assuming some (given or derived) SUSY-breaking terms and a matching to known data on the Standard Model parameters.

- Observables calculators [9–15]; packages which calculate one or more of the following: collider production cross sections (cross section calculators), decay partial widths (decay packages), relic dark matter density (dark matter packages), and indirect/precision observables, such as rare decay branching ratios or Higgs/electroweak observables (constraint packages).

- Monte-Carlo event generators [16–22], which calculate cross sections through explicit statistical simulation of high-energy particle collisions. By including resonance decays, parton showering, hadronisation, and underlying-event effects, fully exclusive final states can be studied, and, for instance, detector simulations interfaced.

- SUSY fitting programs [23, 24] which fit MSSM models to collider-type data.

At the time of writing, the SLHA1 has already, to a large extent, obliterated the need for separately coded (and maintained and debugged) interfaces between many of these codes. Moreover, it has provided users with input and output in a common format, which is more readily comparable and transferable. Finally, the SLHA convention choices are also being adapted for other tasks, such as the SPA project [25]. We believe, therefore, that the SLHA project has been useful, solving a problem that, for experts, is trivial but frequently occurring and tedious to deal with, and which, for non-experts, is an unnecessary head-ache.

However, SLHA1 was designed exclusively with the MSSM with real parameters and R-parity conservation in mind. Some recent public codes [6, 7, 26–30] are either implementing extensions to this base model or are anticipating such extensions. It therefore seems prudent at this time to consider how to extend SLHA1 to deal with more general supersymmetric theories. In particular, we will consider the violation of R-parity, flavour violation and CP-violating phases in the MSSM. We will also consider the next-to-minimal supersymmetric standard model (NMSSM).

There is clearly some tension between the desirable goal of generality of the models covered by the accord and easy implementation for the programs that use it and practicality. A completely general accord would be useless if it were so complicated to implement that none of the relevant programs implemented it. We have made the following agreement for SLHA2: for the MSSM, we will here restrict our attention to *either* CPV or RPV, but not both. We shall work in the Super-CKM/MNS basis throughout (defined in Section 3.1) For the NMSSM, we extend the SLHA1 mixing only to include the new states, with CP, R-parity and flavour still assumed conserved.

Since there is a clear motivation to make the interface as independent of programming languages, compilers, platforms etc, as possible, the SLHA1 is based on the transfer of three different ASCII files (or potentially a character string containing identical ASCII information, if CPU-time constraints are crucial): one for model input, one for spectrum calculator output, and one for decay calculator output. We believe that the advantage of platform, and indeed language independence, outweighs the disadvantage of codes using SLHA1 having to parse input. Indeed, there are tools to assist with this task [31, 32].

Much care was taken in SLHA1 to provide a framework for the MSSM that could easily be extended to the cases listed above. The conventions and switches described here are designed to be a *superset* of the original SLHA1 and so, unless explicitly mentioned in the text, we will assume the conventions of the original SLHA1 [1] implicitly. For instance, all dimensionful parameters quoted in the present paper are assumed to be in the appropriate power of GeV. In a few cases it will be necessary to replace the original conventions. This is clearly remarked upon in all places where it occurs, and the SLHA2 conventions then supersede the SLHA1 ones.

2 Model Selection

To define the general properties of the model, we propose to introduce global switches in the SLHA1 model definition block `MODSEL`, as follows. Note that the switches defined here are in addition to the ones in [1].

`BLOCK MODSEL`

Switches and options for model selection. The entries in this block should consist of an index, identifying the particular switch in the listing below, followed by another integer or real number, specifying the option or value chosen:

`3` : (Default=`0`) Choice of particle content. Switches defined are:

- `0` : MSSM.
- `1` : NMSSM. As defined here.

`4` : (Default=`0`) R-parity violation. Switches defined are:

- `0` : R-parity conserved. This corresponds to the SLHA1.
- `1` : R-parity violated. The blocks defined in Section 3.2 should be present.

`5` : (Default=`0`) CP violation. Switches defined are:

- `0` : CP is conserved. No information even on the CKM phase is used. This corresponds to the SLHA1.
- `1` : CP is violated, but only by the standard CKM phase. All extra SUSY phases assumed zero.
- `2` : CP is violated. Completely general CP phases allowed. Imaginary parts corresponding to the entries in the SLHA1 block `EXTPAR` can be given in `IMEXTPAR` (together with the CKM phase). In the case of additional SUSY flavour violation, imaginary parts of the blocks defined in Section 3.1 should be given, again with the prefix `IM`, which supersede the corresponding entries in `IMEXTPAR`.

`6` : (Default=`0`) Flavour violation. Switches defined are:

- `0` : No (SUSY) flavour violation. This corresponds to the SLHA1.
- `1` : Quark flavour is violated. The blocks defined in Section 3.1.1 should be present.
- `2` : Lepton flavour is violated. The blocks defined in Section 3.1.2 should be present.
- `3` : Lepton and quark flavour is violated. The blocks defined in Sections 3.1.1 and 3.1.2 should both be present.

3 General MSSM

3.1 Flavour Violation

3.1.1 The quark sector and the super-CKM basis

Within the minimal supersymmetric standard model (MSSM), there are two new sources of flavour changing neutral currents (FCNCs), namely 1) contributions arising from quark mixing as in the SM and 2) generic supersymmetric contributions arising through the squark mixing. These generic new sources of flavour violation are a direct consequence of a possible misalignment of quarks and squarks. The severe experimental constraints on flavour violation have no direct explanation in the structure of the unconstrained MSSM which leads to the well-known supersymmetric flavour problem.

The Super-CKM basis of the squarks [33] is very useful in this context because in that basis only physically measurable parameters are present. In the Super-CKM basis the quark mass matrix is diagonal and the squarks are rotated in parallel to their superpartners. Actually, once the electroweak symmetry is broken, a rotation in flavour space (see also Sect.III in [34])

$$D^o \ = \ V_d\, D\,, \qquad U^o \ = \ V_u\, U\,, \qquad \bar{D}^o = \ U_d^*\, \bar{D}\,, \qquad \bar{U}^o = \ U_u^*\, \bar{U}\,, \tag{1}$$

of all matter superfields in the superpotential

$$W \ = \ \epsilon_{ab}\left[(Y_D)_{ij}\, H_1^a Q_i^{b\,o} \bar{D}_j^o + (Y_U)_{ij}\, H_2^b Q_i^{a\,o} \bar{U}_j^{\,o} - \mu H_1^a H_2^b\,,\right] \tag{2}$$

brings fermions from the current eigenstate basis $\{d_L^o, u_L^o, d_R^o, u_R^o\}$ to their mass eigenstate basis $\{d_L, u_L, d_R, u_R\}$:

$$d_L^o = V_d d_L\,, \qquad u_L^o = V_u u_L\,, \qquad d_R^o = U_d d_R\,, \qquad u_R^o = U_u u_R\,, \tag{3}$$

and the scalar superpartners to the basis $\{\tilde{d}_L, \tilde{u}_L, \tilde{d}_R, \tilde{u}_R\}$. Through this rotation, the Yukawa matrices Y_D and Y_U are reduced to their diagonal form $\hat{Y}_D$ and $\hat{Y}_U$:

$$(\hat{Y}_D)_{ii} = (U_d^\dagger Y_D V_d)_{ii} = \sqrt{2}\frac{m_{d\,i}}{v_1}\,, \qquad (\hat{Y}_U)_{ii} = (U_u^\dagger Y_U V_u)_{ii} = \sqrt{2}\frac{m_{u\,i}}{v_2}\,. \tag{4}$$

Tree-level mixing terms among quarks of different generations are due to the misalignment of V_d and V_u which can be expressed via the CKM matrix $V_{\rm CKM} = V_u^\dagger V_d$ [35, 36]; all the vertices $\bar{u}_{L\,i}$–$d_{L\,j}$–W^+ and $\bar{u}_{L\,i}$–$d_{R\,j}$–H^+, $\bar{u}_{R\,i}$–$d_{L\,j}$–H^+ $(i, j = 1, 2, 3)$ are weighted by the elements of the CKM matrix. This is also true for the supersymmetric counterparts of these vertices, in the limit of unbroken supersymmetry.

In the super-CKM basis the 6×6 mass matrices for the up-type and down-type squarks are defined as

$$\mathcal{L}_{\tilde{q}}^{\rm mass} \ = \ -\,\Phi_u^\dagger\, \mathcal{M}_{\tilde{u}}^2\, \Phi_u \ -\Phi_d^\dagger\, \mathcal{M}_{\tilde{d}}^2\, \Phi_d\ , \tag{5}$$

where $\Phi_u = (\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R)^T$ and $\Phi_d = (\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R)^T$. They read:

$$\mathcal{M}_{\tilde{u}}^2 \ = \ \left(\begin{array}{cc} V_{\rm CKM}\, \hat{m}_{\tilde{Q}}^2\, V_{\rm CKM}^\dagger + m_u^2 + D_{u\,LL} & v_2 \hat{T}_U^\dagger - \mu m_u \cot\beta \\ v_2 \hat{T}_U - \mu^* m_u \cot\beta & \hat{m}_{\tilde{u}}^2 + m_u^2 + D_{u\,RR} \end{array}\right)\,, \tag{6}$$

$$\mathcal{M}_{\tilde{d}}^2 = \begin{pmatrix} \hat{m}_{\tilde{Q}}^2 + m_d^2 + D_{d\,LL} & v_1 \hat{T}_D^\dagger - \mu m_d \tan\beta \\ v_1 \hat{T}_D - \mu^* m_d \tan\beta & \hat{m}_{\tilde{d}}^2 + m_d^2 + D_{d\,RR} \end{pmatrix} . \tag{7}$$

In the equations above we introduced the 3×3 matrices

$$\hat{m}_{\tilde{Q}}^2 \equiv V_d^\dagger\, m_{\tilde{Q}}^2\, V_d \,, \quad \hat{m}_{\tilde{u}}^2 \equiv U_u^\dagger\, m_{\tilde{u}}^2\, U_u \,, \quad \hat{m}_{\tilde{d}}^2 \equiv U_d^\dagger\, m_{\tilde{d}}^2\, U_d \,, \tag{8}$$

$$\hat{T}_U \equiv U_u^\dagger\, T_U\, V_u \,, \quad \hat{T}_D \equiv U_d^\dagger\, T_D\, V_d \,, \tag{9}$$

where the un-hatted mass matrices and trilinear interaction matrices are given in the electroweak basis of [1]. The matrices $m_{u,d}$ are the diagonal up-type and down-type quark masses and $D_{f\,LL,RR}$ are the D-terms given by:

$$D_{f\,LL,RR} = \cos 2\beta\, m_Z^2 \left(T_f^3 - Q_f \sin^2\theta_W \right) \mathbb{1}_3 \,, \tag{10}$$

which are also flavour diagonal. Note that the up-type and down-type squark mass matrices in eqs. (6) and (7) cannot be simultaneously flavour-diagonal unless $\hat{m}_{\tilde{Q}}^2$ is flavour-universal (i.e. proportional to the identity in flavour space).

3.1.2 The lepton sector and the super-MNS basis

We also adopt the super-MNS basis in the lepton sector. Neutrino oscillation data have provided a strong indication that neutrinos have masses and that there are flavour-changing charged currents in the leptonic sector. One popular model to produce such effects is the see-saw mechanism, where right-handed neutrinos have both Yukawa couplings with the left-handed leptons and heavy Majorana masses for the right-handed neutrinos [?]. When the heavy neutrinos are integrated out of the effective field theory, one is left with three light approximately left-handed neutrinos which are identified with the ones observed experimentally. There are other models of neutrino masses, for example involving SU(2) Higgs triplets, that, once the triplets have been integrated out, also lead to effective Majorana masses for the neutrinos. Here, we cover all cases that lead to a low energy effective field theory with Majorana neutrino masses and one sneutrino per family. In terms of this low energy effective theory, the lepton mixing phenomenon is analogous to the quark mixing case and so we adapt the conventions defined above to the leptonic case. After electroweak symmetry breaking, the leptonic sector of the MSSM contains the Lagrangian pieces (in 2-component notation)

$$\mathcal{L} = -\frac{1}{2}\bar{\nu}^o (m_\nu) \nu^o - \bar{e}_R^o (m_e) e_L^o + \text{h.c.} + \ldots , \tag{11}$$

where m_ν is a 3×3 symmetric matrix. The current eigenstate basis fields $\{e_L^o, e_R^o, \nu^o\}$ are related to the mass eigenstate ones $\{e_L, e_R, \nu\}$ by

$$e_L^o = V_e e_L, \qquad e_R^o = U_e e_R, \qquad \nu^o = V_\nu \nu. \tag{12}$$

Through this rotation, the mass matrices m_ν and m_e are reduced to their diagonal forms $\hat{m}_\nu$ and $\hat{m}_e$:

$$(\hat{m}_\nu)_{ii} = (V_\nu^T m_\nu V_\nu)_{ii} = m_{\nu_i}, \qquad (\hat{m}_e)_{ii} = (U_e^\dagger m_e V_e)_{ii} = m_{e_i} \ . \tag{13}$$

The equivalent diagonalised charged lepton Yukawa matrix is

$$(\hat{Y}_E)_{ii} = (U_e^\dagger Y_E V_e)_{ii} = \sqrt{2}\frac{m_{ei}}{v_1} \quad . \tag{14}$$

Lepton mixing in the charged current interaction can then be characterised by the MNS matrix $V_{MNS} = V_\nu^\dagger V_e$, which is proportional to $\bar{\nu}_i - e_{Lj} - W^+$ and $\bar{\nu}_i - e_{Rj} - H^+$ couplings. Rotating the interaction eigenstates of the sleptons identically to their leptonic counterparts, we obtain the super-MNS basis for the charged sleptons and the sneutrinos, described by the Lagrangian

$$\mathcal{L}_{\tilde{l}}^{mass} = -\Phi_e^\dagger \mathcal{M}_{\tilde{e}}^2 \Phi_e - \Phi_\nu^\dagger \mathcal{M}_{\tilde{\nu}}^2 \Phi_\nu, \tag{15}$$

where $\Phi_\nu = (\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau)^T$ and $\Phi_e = (\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R)^T$. $\mathcal{M}_{\tilde{e}}^2$ is the 6×6 matrix

$$\mathcal{M}_{\tilde{e}}^2 = \begin{pmatrix} \hat{m}_{\tilde{L}}^2 + m_e^2 + D_{eLL} & v_1 \hat{T}_E^\dagger - \mu m_e \tan\beta \\ v_1 \hat{T}_E - \mu^* m_e \tan\beta & \hat{m}_{\tilde{e}}^2 + m_e^2 + D_{eRR} \end{pmatrix}. \tag{16}$$

$\mathcal{M}_{\tilde{\nu}}^2$ is the 3×3 matrix

$$\mathcal{M}_{\tilde{\nu}}^2 = V_{MNS}\ \hat{m}_{\tilde{L}}^2\ V_{MNS}^\dagger + D_{\nu LL}, \tag{17}$$

where we have neglected neutrino masses in eq. (17) and D_{eLL} and $D_{\nu LL}$ are given in eq. (10). In the equations above we introduced the 3×3 matrices

$$\hat{m}_{\tilde{L}}^2 \equiv V_e^\dagger \, m_{\tilde{L}}^2 \, V_e \, , \quad \hat{m}_{\tilde{e}}^2 \equiv U_e^\dagger \, m_{\tilde{e}}^2 \, U_e \, , \tag{18}$$

$$\hat{T}_E \equiv U_e^\dagger \, T_E \, V_e \, , \tag{19}$$

where the un-hatted mass matrices and trilinear interaction matrices are given in the electroweak basis of [1].

3.1.3 Explicit proposal for SLHA2

As in the SLHA1 [1], for all running parameters in the output of the spectrum file, we propose to use $\overline{\text{DR}}$ definitions. The basis is the super-CKM/MNS basis as defined above, that is the one in which the Yukawa couplings of the SM fermions, given in the $\overline{\text{DR}}$ scheme, are diagonal. Note that the masses and VEVs in eqs. (4), (13), and (14) must thus be the running ones in the $\overline{\text{DR}}$ scheme.

The input for an explicit implementation in a spectrum calculator consists of the following information:

- All input SUSY parameters are given at the scale M_{input} as defined in the SLHA1 block `EXTPAR`. If no M_{input} is present, the GUT scale is used.

- For the SM input parameters, we take the PDG definition: lepton masses are all on-shell. The light quark masses $m_{u,d,s}$ are given at 2 GeV, $m_c(m_c)^{\overline{\rm MS}}$, $m_b(m_b)^{\overline{\rm MS}}$ and $m_t^{\rm on-shell}$. The latter two quantities are already in the SLHA1. The others are added to `SMINPUTS` in the following manner (repeating the SLHA1 parameters for convenience):

  `1` : $\alpha_{\rm em}^{-1}(m_Z)^{\overline{\rm MS}}$. Inverse electromagnetic coupling at the Z pole in the $\overline{\rm MS}$ scheme (with 5 active flavours).

  `2` : G_F. Fermi constant (in units of $\rm GeV^{-2}$).

  `3` : $\alpha_s(m_Z)^{\overline{\rm MS}}$. Strong coupling at the Z pole in the $\overline{\rm MS}$ scheme (with 5 active flavours).

  `4` : m_Z, pole mass.

  `5` : $m_b(m_b)^{\overline{\rm MS}}$. b quark running mass in the $\overline{\rm MS}$ scheme.

  `6` : m_t, pole mass.

  `7` : m_τ, pole mass.

  `8` : m_{ν_3}, pole mass.

  `11` : $m_{\rm e}$, pole mass.

  `12` : m_{ν_1}, pole mass.

  `13` : m_μ, pole mass.

  `14` : m_{ν_2}, pole mass.

  `21` : $m_d(2{\rm GeV})^{\overline{\rm MS}}$. d quark running mass in the $\overline{\rm MS}$ scheme.

  `22` : $m_u(2{\rm GeV})^{\overline{\rm MS}}$. u quark running mass in the $\overline{\rm MS}$ scheme.

  `23` : $m_s(2{\rm GeV})^{\overline{\rm MS}}$. s quark running mass in the $\overline{\rm MS}$ scheme.

  `24` : $m_c(m_c)^{\overline{\rm MS}}$. c quark running mass in the $\overline{\rm MS}$ scheme.

  The FORTRAN format is the same as that of `SMINPUTS` in SLHA1 [1].

- $V_{\rm CKM}$: the input CKM matrix in the PDG parametrisation [37] (exact to all orders), in the block `VCKMIN`. Note that present CKM studies do not precisely define a renormalisation scheme for this matrix since the electroweak effects that renormalise it are highly suppressed and generally neglected. We therefore assume that the CKM elements given by PDG (or by UTFIT and CKMFITTER, the main collaborations that extract the CKM parameters) refer to SM $\overline{\rm MS}$ quantities defined at $Q = m_Z$, to avoid any possible ambiguity. `VCKMIN` should have the following entries:

  `1` : θ_{12} (the Cabibbo angle)

  `2` : θ_{23}

  `3` : θ_{13}

  `4` : δ_{13}

The FORTRAN format is the same as that of `SMINPUTS` above. Note that the three θ angles can all be made to lie in the first quadrant by appropriate rotations of the quark phases.

- $V_{\rm MNS}$: the input MNS matrix, in the block `VMNSIN`. It should have the PDG parameterisation that was used for the quarks (but obviously with data consistent with neutrino oscillation data):

  `1` : $\bar\theta_{12}$ (the solar angle)

  `2` : $\bar\theta_{23}$ (the atmospheric mixing angle)

  `3` : $\bar\theta_{13}$ (currently only has an upper bound)

  `4` : $\bar\delta_{13}$

  The FORTRAN format is the same as that of `SMINPUTS` above.

- $(\hat m^2_{\tilde Q})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde u})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde d})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde L})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde e})^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking masses at the input scale in the super-CKM/MNS basis, as defined above. They will be given in the new blocks `MSQ2IN`, `MSU2IN`, `MSD2IN`, `MSL2IN`, `MSE2IN`, with the FORTRAN format

  ```
  (1x,I2,1x,I2,3x,1P,E16.8,0P,3x,'#',1x,A).
  ```

  where the first two integers in the format correspond to i and j and the double precision number to the soft mass squared. Only the "upper triangle" of these matrices should be given. If diagonal entries are present, these supersede the parameters in the SLHA1 block `EXTPAR`

- $(\hat T_U)^{\overline{\rm DR}}_{ij}$, $(\hat T_D)^{\overline{\rm DR}}_{ij}$, and $(\hat T_E)^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking trilinear couplings at the input scale in the super-CKM/MNS basis, in the same format as the soft mass matrices above. If diagonal entries are present these supersede the A parameters specified in the SLHA1 block `EXTPAR` [1].

For the output, the pole masses are given in block `MASS` as in SLHA1, and the $\overline{\rm DR}$ and mixing parameters as follows:

- $(\hat m^2_{\tilde Q})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde u})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde d})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde L})^{\overline{\rm DR}}_{ij}$, $(\hat m^2_{\tilde e})^{\overline{\rm DR}}_{ij}$: the squark and slepton soft SUSY-breaking masses at scale Q in the super-CKM/MNS basis. Will be given in the new blocks `MSQ2 Q=...`, `MSU2 Q=...`, `MSD2 Q=...`, `MSL2 Q=...`, `MSE2 Q=...`, with formats as the corresponding input blocks `MSX2IN` above.

- $(\hat T_U)^{\overline{\rm DR}}_{ij}$, $(\hat T_D)^{\overline{\rm DR}}_{ij}$, and $(\hat T_E)^{\overline{\rm DR}}_{ij}$: The squark and slepton soft SUSY-breaking trilinear couplings in the super-CKM/MNS basis. Given in the new blocks `TU Q=...`, `TD Q=...`, `TE Q=...`, which supersede the SLHA1 blocks `AD`, `AU`, and `AE`, see [1].

- $(\hat Y_U)^{\overline{\rm DR}}_{ii}$, $(\hat Y_D)^{\overline{\rm DR}}_{ii}$, $(\hat Y_E)^{\overline{\rm DR}}_{ii}$: the diagonal $\overline{\rm DR}$ Yukawas in the super-CKM/MNS basis, with $\hat Y$ defined by eqs. (4) & (14), at the scale Q. Given in the SLHA1 blocks `YU`

Q=..., YD Q=..., YE Q=..., see [1]. Note that although the SLHA1 blocks provide for off-diagonal elements, only the diagonal ones will be relevant here, due to the CKM/MNS rotation.

- The $\overline{\rm DR}$ CKM matrix at the scale Q, in the PDG parametrisation [37]. Will be given in the new block(s) VCKM Q=..., with entries defined as for the input block VCKMIN above.

- The $\overline{\rm DR}$ MNS matrix at the scale Q, again in the PDG parameterisation in the new block VMNS Q=... with entries defined as for the input block VMNSIN above.

- The squark and slepton masses and mixing matrices should be defined as in the existing SLHA1, e.g. extending the $\tilde{t}$, $\tilde{b}$ and $\tilde{e}$ mixing matrices to the 6×6 case. More specifically, the new blocks USQMIX DSQMIX, SELMIX and the 3 by 3 matrix SNUMIX connect the particle codes (=mass-ordered basis) with the super-CKM basis according to the following definition:

$$\begin{pmatrix} 1000001 \\ 1000003 \\ 1000005 \\ 2000001 \\ 2000003 \\ 2000005 \end{pmatrix} = \begin{pmatrix} \tilde{d}_1 \\ \tilde{d}_2 \\ \tilde{d}_3 \\ \tilde{d}_4 \\ \tilde{d}_5 \\ \tilde{d}_6 \end{pmatrix}_{\rm mass-ordered} = \texttt{DSQMIX}_{ij} \begin{pmatrix} \tilde{d}_L \\ \tilde{s}_L \\ \tilde{b}_L \\ \tilde{d}_R \\ \tilde{s}_R \\ \tilde{b}_R \end{pmatrix}_{\rm super-CKM} , \tag{20}$$

$$\begin{pmatrix} 1000002 \\ 1000004 \\ 1000006 \\ 2000002 \\ 2000004 \\ 2000006 \end{pmatrix} = \begin{pmatrix} \tilde{u}_1 \\ \tilde{u}_2 \\ \tilde{u}_3 \\ \tilde{u}_4 \\ \tilde{u}_5 \\ \tilde{u}_6 \end{pmatrix}_{\rm mass-ordered} = \texttt{USQMIX}_{ij} \begin{pmatrix} \tilde{u}_L \\ \tilde{c}_L \\ \tilde{t}_L \\ \tilde{u}_R \\ \tilde{c}_R \\ \tilde{t}_R \end{pmatrix}_{\rm super-CKM} . \tag{21}$$

$$\begin{pmatrix} 1000011 \\ 1000013 \\ 1000015 \\ 2000011 \\ 2000013 \\ 2000015 \end{pmatrix} = \begin{pmatrix} \tilde{e}_1 \\ \tilde{e}_2 \\ \tilde{e}_3 \\ \tilde{e}_4 \\ \tilde{e}_5 \\ \tilde{e}_6 \end{pmatrix}_{\rm mass-ordered} = \texttt{SELMIX}_{ij} \begin{pmatrix} \tilde{e}_L \\ \tilde{\mu}_L \\ \tilde{\tau}_L \\ \tilde{e}_R \\ \tilde{\mu}_R \\ \tilde{\tau}_R \end{pmatrix}_{\rm super-MNS} , \tag{22}$$

$$\begin{pmatrix} 1000012 \\ 1000014 \\ 1000016 \end{pmatrix} = \begin{pmatrix} \tilde{\nu}_1 \\ \tilde{\nu}_2 \\ \tilde{\nu}_3 \end{pmatrix}_{\rm mass-ordered} = \texttt{SNUMIX}_{ij} \begin{pmatrix} \tilde{\nu}_{e_L} \\ \tilde{\nu}_{\mu_L} \\ \tilde{\nu}_{\tau_L} \end{pmatrix}_{\rm super-MNS} . \tag{23}$$

Note! A potential for inconsistency arises if the masses and mixings are not calculated in the same way, e.g. if radiatively corrected masses are used with tree-level mixing matrices. In this case, it is possible that the radiative corrections to the masses shift the mass ordering relative to the tree-level. This is especially relevant when near-degenerate masses occur in the spectrum and/or when the radiative corrections are large. In these cases, explicit care must be taken especially by the program writing the spectrum, but also by the one reading it, to properly arrange the rows in the order of the mass spectrum actually used.

3.2 R-Parity Violation

Throughout this Section we shall use the same basis as above, i.e. the Super-CKM/MNS basis, in which the Yukawa couplings of the quark and lepton fields are diagonal.

We write the superpotential of R-parity violating interactions in the notation of [1] as

$$\begin{aligned} W_{RPV} &= \epsilon_{ab}\left[\frac{1}{2}\lambda_{ijk}L_i^a L_j^b \bar{E}_k + \lambda'_{ijk}L_i^a Q_j^{bx}\bar{D}_{kx} - \kappa_i L_i^a H_2^b\right] \\ &\quad +\frac{1}{2}\lambda''_{ijk}\epsilon^{xyz}\bar{U}_{ix}\bar{D}_{jy}\bar{D}_{kz}, \end{aligned} \tag{24}$$

where $x, y, z = 1, \ldots, 3$ are fundamental $\mathrm{SU}(3)_C$ indices and ϵ^{xyz} is the totally antisymmetric tensor in 3 dimensions with $\epsilon^{123} = +1$. In eq. (24), λ_{ijk}, λ'_{ijk} and κ_i break lepton number, whereas λ''_{ijk} violate baryon number. To ensure proton stability, either lepton number conservation or baryon number conservation is usually still assumed, resulting in either $\lambda_{ijk} = \lambda'_{ijk} = \kappa_i = 0$ or $\lambda''_{ijk} = 0$ for all $i, j, k = 1, 2, 3$.

The trilinear R-parity violating terms in the soft SUSY-breaking potential are

$$\begin{aligned} V_{3,\mathrm{RPV}} &= \epsilon_{ab}\left[\frac{1}{2}(T)_{ijk}\tilde{L}_{iL}^a\tilde{L}_{jL}^b\tilde{e}_{kR}^* + (T')_{ijk}\tilde{L}_{iL}^a\tilde{Q}_{jL}^b\tilde{d}_{kR}^*\right] \\ &\quad +\frac{1}{2}(T'')_{ijk}\epsilon_{xyz}\tilde{u}_{iR}^{x*}\tilde{d}_{jR}^{y*}\tilde{d}_{kR}^{z*} + \mathrm{h.c.} \quad . \end{aligned} \tag{25}$$

Note that we do not factor out the λ couplings (e.g. as in $T_{ijk}/\lambda_{ijk} \equiv A_{\lambda,ijk}$) in order to avoid potential problems with $\lambda_{ijk} = 0$ but $T_{ijk} \neq 0$. This usage is consistent with the convention for the R-conserving sector elsewhere in this report.

The additional bilinear soft SUSY-breaking potential terms are

$$V_{RPV2} = -\epsilon_{ab}D_i\tilde{L}_{iL}^a H_2^b + \tilde{L}_{iaL}^\dagger m^2_{\tilde{L}_i H_1} H_1^a + \mathrm{h.c.} \tag{26}$$

and are all lepton number violating.

When lepton number is broken, the sneutrinos may acquire vacuum expectation values (VEVs) $\langle\tilde{\nu}_{e,\mu,\tau}\rangle \equiv v_{e,\mu,\tau}/\sqrt{2}$. The SLHA1 defined the VEV v, which at tree level is equal to $2m_Z/\sqrt{g^2+g'^2} \sim 246$ GeV; this is now generalised to

$$v = \sqrt{v_1^2 + v_2^2 + v_\mathrm{e}^2 + v_\mu^2 + v_\tau^2}\ . \tag{27}$$

The addition of sneutrino VEVs allows for various different definitions of $\tan\beta$, but we here choose to keep the SLHA1 definition $\tan\beta = v_2/v_1$.

3.2.1 Input/Output Blocks

For R-parity violating parameters and couplings, the input will occur in `BLOCK RV#IN`, where the '`#`' character should be replaced by the name of the relevant output block given below (thus, for example, `BLOCK RVLAMBDAIN` would be the input block for λ_{ijk}). Default inputs for all R-parity violating couplings are zero. The inputs are given at scale $M_{\rm input}$, as described in SLHA1 (again, if no $M_{\rm input}$ is given, the GUT scale is assumed), and follow the output format given below, with the omission of `Q= ...`. The dimensionless couplings $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ are included in the SLHA2 conventions as `BLOCK RVLAMBDA, RVLAMBDAP, RVLAMBDAPP Q= ...` respectively. The output standard should correspond to the FORTRAN format

```
(1x,I2,1x,I2,1x,I2,3x,1P,E16.8,0P,3x,'#',1x,A).
```

where the first three integers in the format correspond to i, j, and k and the double precision number to the coupling itself. $T_{ijk}, T'_{ijk}, T''_{ijk}$ are included as `BLOCK RVT, RVTP, RVTPP Q= ...` in the same conventions as $\lambda_{ijk}, \lambda'_{ijk}, \lambda''_{ijk}$ (except for the fact that they are measured in GeV). The bilinear superpotential and soft SUSY-breaking terms κ_i, D_i, and $m^2_{\tilde{L}_i H_1}$ are contained in `BLOCK RVKAPPA, RVD, RVMLH1SQ Q= ...` respectively as

```
(1x,I2,3x,1P,E16.8,0P,3x,'#',1x,A).
```

in FORTRAN format. Sneutrino VEV parameters v_i are given as `BLOCK SNVEV Q= ...` in an identical format, where the integer labels `1`$=e$, `2`$=\mu$, `3`$=\tau$ respectively and the double precision number gives the numerical value of the VEV in GeV. The input and output blocks for R-parity violating couplings are summarised in Tab. 1.

As for the R-conserving MSSM, the bilinear terms (both SUSY-breaking and SUSY-respecting ones, including μ) and the VEVs are not independent parameters. They become related by the condition of electroweak symmetry breaking. Thus, in the SLHA1, one had the possibility *either* to specify $m^2_{H_1}$ and $m^2_{H_2}$ *or* μ and m^2_A. This carries over to the RPV case, where not all the parameters in the input blocks `RPV...IN` in Tab. 1 can be given simultaneously. Of the last 4 blocks only 3 are independent. One block is determined by minimising the Higgs-sneutrino potential. We do not insist on a particular choice for which of `RVKAPPAIN`, `RVDIN`, `RVSNVEVIN`, and `RVMLH1SQIN` to leave out, but leave it up to the spectrum calculators to accept one or more combinations.

3.2.2 Particle Mixing

The mixing of particles can change when L is violated. Phenomenological constraints can often imply that any such mixing has to be small. It is therefore possible that some programs may ignore the mixing in their output. In this case, the mixing matrices from SLHA1 should suffice. However, in the case that mixing is considered to be important and included in the output, we here present extensions to the mixing blocks from SLHA1 appropriate to the more general case.

In general, the neutrinos mix with the neutralinos. This requires a change in the definition of the 4×4 neutralino mixing matrix N to a 7×7 matrix. The Lagrangian contains

Input block	Output block	data
`RVLAMBDAIN`	`RVLAMBDA`	$i\ j\ k\ \lambda_{ijk}$
`RVLAMBDAPIN`	`RVLAMBDAP`	$i\ j\ k\ \lambda'_{ijk}$
`RVLAMBDAPPIN`	`RVLAMBDAPP`	$i\ j\ k\ \lambda''_{ijk}$
`RVTIN`	`RVT`	$i\ j\ k\ T_{ijk}$
`RVTPIN`	`RVTP`	$i\ j\ k\ T'_{ijk}$
`RVTPPIN`	`RVTPP`	$i\ j\ k\ T''_{ijk}$
NB: One of the following `RV...IN` blocks must be left out: (which one up to user and RGE code)		
`RVKAPPAIN`	`RVKAPPA`	$i\ \kappa_i$
`RVDIN`	`RVD`	$i\ D_i$
`RVSNVEVIN`	`RVSNVEV`	$i\ v_i$
`RVMLH1SQIN`	`RVMLH1SQ`	$i\ m^2_{\tilde{L}_iH_1}$

Table 1: Summary of R-parity violating SLHA2 data blocks. All output parameters are to be given in the Super-CKM/MNS basis, but input parameters should be given in the current eigenstate basis. Only 3 out of the last 4 blocks are independent. Which block to leave out of the input is in principle up to the user, with the caveat that a given spectrum calculator may not accept all combinations. See text for a precise definition of the format.

the (symmetric) neutralino mass matrix as

$$\mathcal{L}^{\mathrm{mass}}_{\tilde{\chi}^0} = -\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 + \mathrm{h.c.}\ , \tag{28}$$

in the basis of 2–component spinors $\tilde{\psi}^0 = (\nu_e, \nu_\mu, \nu_\tau, -i\tilde{b}, -i\tilde{w}^3, \tilde{h}_1, \tilde{h}_2)^T$. We define the unitary 7×7 neutralino mixing matrix N (block `RVNMIX`), such that:

$$-\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\frac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0}\ , \tag{29}$$

where the 7 (2–component) generalised neutralinos $\tilde{\chi}_i$ are defined strictly mass-ordered, i.e. with the 1^{st},2^{nd},3^{rd} lightest corresponding to the mass entries for the PDG codes `12`, `14`, and `16`, and the four heaviest to the PDG codes `1000022`, `1000023`, `1000025`, and `1000035`.

Note! although these codes are normally associated with names that imply a specific flavour content, such as code `12` being ν_{e} and so forth, it would be exceedingly complicated to maintain such a correspondence in the context of completely general mixing, hence we do not make any such association here. The flavour content of each state, i.e. of each PDG number, is in general <u>only</u> defined by its corresponding entries in the mixing matrix `RVNMIX`. Note, however, that the flavour basis is ordered so as to reproduce the usual associations in the trivial case (modulo the unknown flavour composition of the neutrino mass eigenstates).

In the limit of CP conservation, the default convention is that N be a real symmetric matrix and the neutralinos may have an apparent negative mass. The minus sign may be removed by phase transformations on $\tilde{\chi}^0_i$ as explained in SLHA1 [1].

Charginos and charged leptons may also mix in the case of L-violation. In a similar spirit to the neutralino mixing, we define

$$\mathcal{L}^{\rm mass}_{\tilde\chi^+} = -\frac{1}{2}\tilde\psi^{-T}\mathcal{M}_{\tilde\psi^+}\tilde\psi^+ + \text{h.c.}\ , \tag{30}$$

in the basis of 2–component spinors $\tilde\psi^+ = (e^+, \mu^+, \tau^+, -i\tilde w^+, \tilde h_2^+)^T$, $\tilde\psi^- = (e^-, \mu^-, \tau^-, -i\tilde w^-, \tilde h_1^-)^T$ where $\tilde w^\pm = (\tilde w^1 \mp \tilde w^2)/\sqrt{2}$. Note that, in the limit of no RPV the lepton fields are mass eigenstates.

We define the unitary 5×5 charged fermion mixing matrices U, V, blocks `RVUMIX`, `RVVMIX`, such that:

$$-\frac{1}{2}\tilde\psi^{-T}\mathcal{M}_{\tilde\psi^+}\tilde\psi^+ = -\frac{1}{2}\underbrace{\tilde\psi^{-T}U^T}_{\tilde\chi^{-T}}\underbrace{U^*\mathcal{M}_{\tilde\psi^+}V^\dagger}_{\text{diag}(m_{\tilde\chi^+})}\underbrace{V\tilde\psi^+}_{\tilde\chi^+}\ , \tag{31}$$

where $\tilde\chi_i^\pm$ are defined as strictly mass ordered, i.e. with the 3 lightest states corresponding to the PDG codes `11`, `13`, and `15`, and the two heaviest to the codes `1000024`, `1000037`. As for neutralino mixing, the flavour content of each state is in no way implied by its PDG number, but is only defined by its entries in `RVUMIX` and `RVVMIX`. Note, however, that the flavour basis is ordered so as to reproduce the usual associations in the trivial case.

In the limit of CP conservation, U, V are be chosen to be real by default.

CP-even Higgs bosons mix with sneutrinos in the limit of CP symmetry. We write the neutral scalars as $\phi_i^0 \equiv \sqrt{2}\text{Re}\left\{(H_1^0, H_2^0, \tilde\nu_e, \tilde\nu_\mu, \tilde\nu_\tau)^T\right\}$

$$\mathcal{L} = -\frac{1}{2}\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 \tag{32}$$

where $\mathcal{M}^2_{\phi^0}$ is a 5×5 symmetric mass matrix.

One solution is to define the unitary 5×5 mixing matrix $\aleph$ (block `RVHMIX`) by

$$-\phi^{0T}\mathcal{M}^2_{\phi^0}\phi^0 = -\underbrace{\phi^{0T}\aleph^T}_{\Phi^{0T}}\underbrace{\aleph^*\mathcal{M}^2_{\phi^0}\aleph^\dagger}_{\text{diag}(m^2_{\Phi^0})}\underbrace{\aleph\phi^0}_{\Phi^0}\ , \tag{33}$$

where $\Phi^0 \equiv (H^0, h^0, \tilde\nu_1, \tilde\nu_2, \tilde\nu_3)$ are the mass eigenstates (note that we have here labelled the states by what they should tend to in the R-parity conserving limit, and that this ordering is still under debate, hence should be considered preliminary for the time being).

CP-odd Higgs bosons mix with the imaginary components of the sneutrinos: We write these neutral pseudo-scalars as $\bar\phi_i^0 \equiv \sqrt{2}\text{Im}\left\{(H_1^0, H_2^0, \tilde\nu_e, \tilde\nu_\mu, \tilde\nu_\tau)^T\right\}$

$$\mathcal{L} = -\frac{1}{2}\bar\phi^{0T}\mathcal{M}^2_{\bar\phi^0}\bar\phi^0 \tag{34}$$

where $\mathcal{M}^2_{\bar\phi^0}$ is a 5×5 symmetric mass matrix. We define the 4×5 mixing matrix $\bar\aleph$ (block `RVAMIX`) by

$$-\bar\phi^{0T}\mathcal{M}^2_{\bar\phi^0}\bar\phi^0 = -\underbrace{\bar\phi^{0T}\bar\aleph^T}_{\bar\Phi^{0T}}\underbrace{\bar\aleph^*\mathcal{M}^2_{\bar\phi^0}\bar\aleph^\dagger}_{\text{diag}(m^2_{\bar\Phi^0})}\underbrace{\bar\aleph\bar\phi^0}_{\bar\Phi^0}\ , \tag{35}$$

where $\bar{\Phi}^0 \equiv (A^0, \tilde{\nu}_1, \tilde{\nu}_2, \tilde{\nu}_3)$ are the mass eigenstates. The Goldstone boson G^0 (the "5th component") has been explicitly left out and the remaining 4 rows form a set of orthonormal vectors. As for the CP-even sector this specific choice of basis ordering is still preliminary.

If the blocks `RVHMIX, RVAMIX` are present, they *supersede* the SLHA1 `ALPHA` variable/block.

The charged sleptons and charged Higgs bosons also mix in the $8 times 8$ mass squared matrix $\mathcal{M}^2_{\phi^\pm}$ by a 7×8 matrix C (block `RVLMIX`):

$$\mathcal{L} = -\underbrace{(h_1^-, h_2^{+*}, \tilde{e}_{L_i}, \tilde{e}_{R_j}) C^T}_{(H^-, \tilde{e}_\alpha)} \underbrace{C^* \mathcal{M}^2_{\phi^\pm} C^T}_{\mathrm{diag}(\mathcal{M}^2_{\Phi^\pm})} C^* \begin{pmatrix} h_1^{-*} \\ h_2^+ \\ \tilde{e}^*_{L_k} \\ \tilde{e}^*_{R_l} \end{pmatrix} \tag{36}$$

where in eq. (36), $i, j, k, l \in \{1, 2, 3\}$, $\alpha, \beta \in \{1, \ldots, 6\}$, the non-braced product on the right hand side is equal to $(H^+, \tilde{e}^*_\beta)$, and the Goldstone bosons $G^\pm$ (the "8th components") have been explicitly left out and the remaining 7 rows form a set of orthonormal vectors.

There may be contributions to down-squark mixing from R-parity violation. However, this only mixes the six down-type squarks amongst themselves and so is identical to the effects of flavour mixing. This is covered in Section 3.1 (along with other forms of flavour mixing).

3.3 CP Violation

When adding CP violation to mixing matrices and MSSM parameters, the SLHA1 blocks are understood to contain the real parts of the relevant parameters. The imaginary parts should be provided with exactly the same format, in a separate block of the same name but prefaced by `IM`. The defaults for all imaginary parameters will be zero. Thus, for example, `BLOCK IMAU, IMAD, IMAE, Q= ...` would describe the imaginary parts of the trilinear soft SUSY-breaking scalar couplings. For input, `BLOCK IMEXTPAR` may be used to provide the relevant imaginary parts of soft SUSY-breaking inputs. In cases where the definitions of the current paper supersedes the SLHA1 input and output blocks, completely equivalent statements apply.

The Higgs sector mixing changes when CP symmetry is broken, since the CP-even and CP-odd Higgs states mix. Writing the neutral scalars as $\phi_i^0 \equiv \sqrt{2}(\mathrm{Re}\{H_1^0\}, \mathrm{Re}\{H_2^0\}, \mathrm{Im}\{H_1^0\}, \mathrm{Im}\{H_2^0\})$ we define the 3×4 mixing matrix S (blocks `CVHMIX` and `IMCVHMIX`) by

$$-\phi^{0T} \mathcal{M}^2_{\phi^0} \phi^0 = -\underbrace{\phi^{0T} S^T}_{\Phi^{0T}} \underbrace{S^* \mathcal{M}^2_{\phi^0} S^\dagger}_{\mathrm{diag}(m^2_{\Phi^0})} \underbrace{S \phi^0}_{\Phi^0} \ , \tag{37}$$

where $\Phi^0 \equiv (H_1^0, H_2^0, H_3^0)$ are the mass eigenstates and the Goldstone boson G^0 (the "4th component") has been explicitly left out More explicitely, S is defined as

$$S := (R|0) \cdot T \tag{38}$$

where

$$(R|0) := \begin{pmatrix} r_{11} & r_{12} & r_{13} & 0 \\ r_{21} & r_{22} & r_{23} & 0 \\ r_{31} & r_{32} & r_{33} & 0 \end{pmatrix} \text{ with } \begin{pmatrix} H_1^0 \\ H_2^0 \\ H_3^0 \end{pmatrix} = \begin{pmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{pmatrix} \begin{pmatrix} h \\ H \\ A \end{pmatrix}_{\text{tree}} \tag{39}$$

and

$$T := \begin{pmatrix} -\sin\alpha & \cos\alpha & 0 & 0 \\ \cos\alpha & \sin\alpha & 0 & 0 \\ 0 & 0 & -\sin\beta & \cos\beta \\ 0 & 0 & \cos\beta & \sin\beta \end{pmatrix} \text{ with } \begin{pmatrix} h \\ H \\ A \\ G \end{pmatrix}_{\text{tree}} = T \cdot \phi^0 \ . \tag{40}$$

Here α is the tree-level mixing angle in the CP-even Higgs sector, and R is the unitary matrix relating the tree-level mass eigenstates with the higher-order corrected mass eigenstates (see, however, Ref. [30]). In order to reconstruct R from the matrix S given in the accord, the angle α is needed. This should be given in the SLHA1 `BLOCK ALPHA`, but we emphasize that it should here be the tree-level angle (while the higher-order corrections are now included in the matrix S).

We associate the following PDG codes with these states, in strict mass order *regardless* of CP-even/odd composition: H_1^0: 25, H_2^0: 35, H_3^0: 36. That is, even though the PDG reserves code 36 for the CP-odd state, we do not maintain such a labelling here, nor one that reduces to it. This means one does have to exercise some caution when taking the CP conserving limit.

4 The NMSSM

The first question to be addressed in defining universal conventions for the Next-to-Minimal Supersymmetric Standard Model (henceforth NMSSM) is just what field content and which couplings this name applies to. The field content is already fairly well agreed upon; we shall here define the NMSSM as having exactly the field content of the MSSM with the addition of one gauge singlet chiral superfield. As to couplings and parameterisations, several definitions exist in the literature (REFERENCES nMSSM, NMSSM, ...). Rather than adopting a particular one, or treating each special case separately, below we choose instead to work at the most general level. Any particular special case can then be obtained by setting different combinations of couplings to zero. For the time being, however, we do specialize to the SLHA1-like case without CP violation, R-parity violation, or flavour violation.

4.1 Conventions

In addition to the MSSM terms, the most general CP conserving NMSSM superpotential contains (extending the notation of SLHA1):

$$W_{NMSSM} = -\epsilon_{ab}\lambda S H_1^a H_2^b + \frac{1}{3}\kappa S^3 + \mu' S^2 + \xi_F S \ , \tag{41}$$

where a non-zero λ in combination with a VEV $\langle S\rangle$ of the singlet generates a contribution to the effective μ term $\mu_{\rm eff} = \mu + \lambda\langle S\rangle$. Usually, the "ordinary" μ term which appears here (from the MSSM superpotential) is taken to be zero in the NMSSM, yielding $\mu_{\rm eff} = \lambda\langle S\rangle$. The sign of the λ term in eq. (41) coincides with the one in [15, 29] where the Higgs doublet superfields appear in opposite order. The remaining terms represent a general cubic potential for the singlet; κ is dimensionless, μ' has dimension of mass, and ξ_F has dimension of mass squared. The additional soft SUSY-breaking terms relevant in the NMSSM are

$$V_{\rm soft} = m_{\rm S}^2|S|^2 + (-\epsilon_{ab}\lambda A_\lambda S H_1^a H_2^b + \frac{1}{3}\kappa A_\kappa S^3 + B'\mu' S^2 + \xi_S S + \text{h.c.}) \ . \qquad (42)$$

As usual, the minimisation equations imposed by electroweak symmetry breaking imply that we can trade the soft masses for M_Z, $\tan\beta$, and $\mu_{\rm eff}$. At tree level, the input parameters relevant for the Higgs sector of the NMSSM can thus be chosen as

$$\tan\beta \ = \ \langle H_2\rangle \,/\, \langle H_1\rangle \,, \ \mu, \ m_3^2, \ \lambda, \ \kappa, \ A_\lambda, \ A_\kappa, \ \lambda\langle S\rangle \,, \ \mu', \ B', \ \xi_F, \ \xi_S \ . \qquad (43)$$

If the MSSM μ term is not zero, it should be given in `EXTPAR` entry `23`, as in SLHA1 [1]. The corresponding soft parameter m_3^2 is given in `EXTPAR` entry `24`, in the form of $m_A^2 = m_3^2/(\cos\beta\sin\beta)$. Note that, in the NMSSM, m_A^2 is simply an effective parameter and is not directly related to any physical particle mass.

4.2 Input/Output Blocks

Firstly, as described above in Section 2, `BLOCK MODSEL` should contain the switch 3 with value 1, corresponding to the choice of the NMSSM particle content.

Further, new entries in `BLOCK EXTPAR` have been defined for the NSSM specific parameters, as follows:

`BLOCK EXTPAR`

NMSSM Parameters

- `61` : λ. Superpotential trilinear Higgs SH_2H_1 coupling.
- `62` : κ. Superpotential cubic S coupling.
- `63` : A_λ. Soft trilinear Higgs SH_2H_1 coupling.
- `64` : A_κ. Soft cubic S coupling.
- `65` : $\mu_{\rm eff} = \lambda\langle S\rangle + \mu$, with μ normally zero in the NMSSM.
- `66` : ξ_F. Superpotential linear S coupling.
- `67` : ξ_S. Soft linear S coupling.
- `68` : μ'. Superpotential quadratic S coupling.

69 : B'. Soft quadratic S coupling.

In all cases, these parameters should be assumed zero if absent. For non-zero values, signs can be either positive or negative. As noted above, the meaning of the already existing entries EXTPAR 23 and 24 (the MSSM μ parameter and corresponding soft term) are maintained, which allows, in principle, for non zero values for both μ and $\langle S\rangle$. The reason for choosing $\mu_{\rm eff}$ rather than $\langle S\rangle$ as input parameter 65 is that it allows more easily to recover the MSSM limit λ, $\kappa \to 0$, $\langle S\rangle \to \infty$ with $\lambda \langle S\rangle$ fixed.

Proposed PDG codes for the new states in the NMSSM (to be used in the BLOCK MASS and the decay files, see also Section 5) are

45	for the third CP-even Higgs boson,
46	for the second CP-odd Higgs boson,
1000045	for the fifth neutralino.

4.3 Particle Mixing

In the CP-conserving NMSSM, the diagonalisation of the 3×3 mass matrix in the CP-even Higgs sector can be performed by an orthogonal matrix S_{ij}. The (neutral) CP-even Higgs weak eigenstates are numbered by $\phi_i^0 \equiv \sqrt{2}\mathrm{Re}\left\{(H_1^0, H_2^0, S)^T\right\}$. If Φ_i are the mass eigenstates (ordered in mass), the convention is $\Phi_i = S_{ij}\phi_j^0$. The elements of S_{ij} should be given in a BLOCK NMHMIX, in the same format as the mixing matrices in SLHA1.

In the MSSM limit (λ, $\kappa \to 0$, and parameters such that $h_3 \sim S_R$) the elements of the first 2×2 sub-matrix of S_{ij} are related to the MSSM angle α as

$$\begin{aligned} S_{11} &\sim \cos\alpha \ , & S_{21} &\sim \sin\alpha \ , \\ S_{12} &\sim -\sin\alpha \ , & S_{22} &\sim \cos\alpha \ . \end{aligned}$$

In the CP-odd sector the weak eigenstates are $\bar\phi_i^0 \equiv \sqrt{2}\mathrm{Im}\left\{(H_1^0, H_2^0, S)^T\right\}$. We define the 2×3 mixing matrix P (block NMAMIX) by

$$-\bar\phi^{0T}\mathcal{M}^2_{\bar\phi^0}\bar\phi^0 = -\underbrace{\bar\phi^{0T}P^T}_{\bar\Phi^{0T}}\underbrace{P\mathcal{M}^2_{\bar\phi^0}P^T}_{\mathrm{diag}(m^2_{\bar\Phi^0})}\underbrace{P\bar\phi^0}_{\bar\Phi^0} \ , \tag{44}$$

where $\bar\Phi^0 \equiv (A_1^0, A_2^0)$ are the mass eigenstates ordered in mass and the Goldstone boson G^0 (the "3rd component") has been explicitly left out and the remaining 2 rows form a set of orthonormal vectors. Hence, $\bar\Phi_i = P_{ij}\bar\phi_j^0$. An updated version NMHDECAY2.2+ [29] will follow these conventions.

If NMHMIX, NMAMIX blocks are present, they *supersede* the SLHA1 ALPHA variable/block.

The neutralino sector of the NMSSM requires a change in the definition of the 4×4 neutralino mixing matrix N to a 5×5 matrix. The Lagrangian contains the (symmetric) neutralino mass matrix as

$$\mathcal{L}^{\rm mass}_{\tilde\chi^0} = -\frac{1}{2}\tilde\psi^{0T}\mathcal{M}_{\tilde\psi^0}\tilde\psi^0 + \mathrm{h.c.} \ , \tag{45}$$

Table 2: SM fundamental particle codes, with extended Higgs sector. Names in parentheses correspond to the MSSM labelling of states.

Code	Name	Code	Name	Code	Name
1	d	11	e^-	21	g
2	u	12	ν_e	22	γ
3	s	13	μ^-	23	Z^0
4	c	14	ν_μ	24	W^+
5	b	15	τ^-		
6	t	16	ν_τ		
25	H_1^0 (h^0)	35	H_2^0 (H^0)	45	H_3^0
36	A_1^0 (A^0)	46	A_2^0		
37	H^+	39	G (graviton)		

in the basis of 2–component spinors $\tilde{\psi}^0 = (-i\tilde{b},\, -i\tilde{w}^3,\, \tilde{h}_1,\, \tilde{h}_2,\, \tilde{s})^T$. We define the unitary 5×5 neutralino mixing matrix N (block `NMNMIX`), such that:

$$-\frac{1}{2}\tilde{\psi}^{0T}\mathcal{M}_{\tilde{\psi}^0}\tilde{\psi}^0 = -\frac{1}{2}\underbrace{\tilde{\psi}^{0T}N^T}_{\tilde{\chi}^{0T}}\underbrace{N^*\mathcal{M}_{\tilde{\psi}^0}N^\dagger}_{\mathrm{diag}(m_{\tilde{\chi}^0})}\underbrace{N\tilde{\psi}^0}_{\tilde{\chi}^0}\ , \tag{46}$$

where the 5 (2–component) neutralinos $\tilde{\chi}_i$ are defined such that the absolute value of their masses increase with i, cf. SLHA1 [1].

5 PDG Codes and Extensions

Listed in Tab. 2 are the PDG codes for extended Higgs sectors and Standard Model particles, extended to include the NMSSM Higgs sector. Tab. 3 contains the codes for the spectrum of superpartners, extended to include the extra NMSSM neutralino as well as a possible mass splitting between the scalar and pseudoscalar sneutrinos. Note that these extensions are not officially endorsed by the PDG at this time — however, neither are they currently in use for anything else. Codes for other particles may be found in [37, chp. 33].

6 Conclusion and Outlook

We deduce from the number of programs using it, that the SLHA1 has been a success. Programs utilising loop-improved tree-level MSSM information have been readily been passing the relevant information to each other. At the time of writing of the SLHA1, there were already many codes that used such information. This had several advantages: there was a high motivation from program authors to produce and implement the accord accurately and quickly, and perhaps more importantly, the SLHA1 was tested "in anger" in diverse situations as it was being written.

Table 3: Sparticle codes in the extended MSSM. Note that two mass eigenstate numbers are assigned for each of the sneutrinos $\tilde{\nu}_{iL}$, corresponding to the possibility of a mass splitting between the pseudoscalar and scalar components.

Code	Name	Code	Name	Code	Name
1000001	$\tilde{d}_L$	1000011	$\tilde{e}_L$	1000021	$\tilde{g}$
1000002	$\tilde{u}_L$	1000012	$\tilde{\nu}_{1eL}$	1000022	χ_1^0
1000003	$\tilde{s}_L$	1000013	$\tilde{\mu}_L$	1000023	χ_2^0
1000004	$\tilde{c}_L$	1000014	$\tilde{\nu}_{1\mu L}$	1000024	$\chi_1^\pm$
1000005	$\tilde{b}_1$	1000015	$\tilde{\tau}_1$	1000025	χ_3^0
1000006	$\tilde{t}_1$	1000016	$\tilde{\nu}_{1\tau L}$	1000035	χ_4^0
		1000017	$\tilde{\nu}_{2eL}$	1000045	χ_5^0
		1000018	$\tilde{\nu}_{2\mu L}$	1000037	$\chi_2^\pm$
		1000019	$\tilde{\nu}_{2\tau L}$	1000039	$\tilde{G}$ (gravitino)
2000001	$\tilde{d}_R$	2000011	$\tilde{e}_R$		
2000002	$\tilde{u}_R$				
2000003	$\tilde{s}_R$	2000013	$\tilde{\mu}_R$		
2000004	$\tilde{c}_R$				
2000005	$\tilde{b}_2$	2000015	$\tilde{\tau}_2$		
2000006	$\tilde{t}_2$				

We find ourselves in a slightly different situation in terms of the SLHA2. There is at most one public program that utilises information in any of the NMSSM, CP-violating MSSM, R-parity violating or non-trivial flavour violating scenarios. Thus we do not have the benefit of on-line testing of the proposed accord and the strong motivation that was present for implementation and writing of the original accord. Nevertheless, we have information that several almost-finished codes are awaiting the publication of SLHA2 in order to publish their first official public releases. We also have experience of what worked well in SLHA1 (and what didn't work very well in the initial formulation and needed to be changed). We have adhered to the principle of backward compatibility wherever feasible so that all of the codes that have already implemented SLHA1 do not have to suddenly re-code their interface to it. We can therefore have some hope that the conventions and agreements reached within this paper constitute a practical solution that will prove useful (and used) for SUSY particle phenomenology.

There are of course many issues not addressed by SLHA1 or SLHA2. Aside from the issue of extended models, there are the following outstanding issues:

- How spin information could be transmitted within the decay information detailed in the SLHA1, perhaps by listing spin density matrices.

- How Feynman rules should be presented for codes which perform radiative corrections. Presently, tree-level improved information is typically passed, but Feynman rules typically have additional levels of ambiguity: regularisation and renormalisation schemes as well as gauge dependence, for instance.

- An estimate of theoretical errors in the entries.

Such issues could potentially be discussed in future Les Houches workshops and other meetings. Aside from the actual conventions agreed in the SLHA2, there is an associated program being developed that will efficiently parse and access all of the relevant information contained therein [?].

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